Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 67 (2018) 493 – 497
www.elsevier.com/locate/procedia

11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '17

Effect of the rolling temperature on hot formability of ZAM100 magnesium alloy

Mohamad El Mehtedi[a,*], Alessio D'Orazio[a], Archimede Forcellese[a], Massimiliano Pieralisi[a], Michela Simoncini[b]

[a]*Università Politecnica delle Marche, Via Brecce Bianche, Ancona 60100, Italy*
[b]*Università degli Studi eCampus, Via Isimabrdi 10, Novedrate (Como) 22060, Italy*

* Corresponding author. Tel.: +39-071-220-4731 ; fax: +39-071-220-4801. *E-mail address:* elmehtedi@univpm.it

Abstract

Magnesium alloy sheets are usually obtained by complex processing cycles including hot rolling operations. Temperature of the final stage of rolling strongly affects the microstructure and, consequently, the hot formability of the sheets. In this framework, the present work aims at investigating the effect of the rolling temperature on the hot formability of the innovative magnesium alloy ZAM100. To this purpose, two different rolling temperatures were used and hot formability was investigated by tensile tests performed in extended ranges of temperature and strain rate. The flow curves were analyzed in order to obtain constitutive models of hot formability.

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Magnesium alloy; Mechanical properties; Hot rolling; Formability.

1. Introduction

In the last years, environmental related topics have awaken the sensitivity of car manufactures and large efforts have been made to reduce the CO_2 emissions in developing new car models. In particular, lightweight materials, that are used in reducing the body car weight, lead to a reduction in fuel consumption and gas emissions; this gives cost and energy savings as well as high quality and environmental respect. Recently, magnesium alloys have shown their high potential for lightweight structural components in automotive applications owing to the excellent properties in terms of low density and high specific strength [1]. Unfortunately, their HCP crystal structure, in which dislocation movement is restricted only in the basal plane, makes magnesium alloys very difficult to deform at room temperature. In fact, HCP metals does not have enough independent slip systems to deform without extensive occurrence of twinning. The formability of Mg alloys can be increased by deforming at high temperatures. As well known, high temperature (above 225°C) causes additional slip systems to become activated, thus conferring to these alloys an acceptable ductility [2-6]. Most of the studies dealing with magnesium alloys, such as AZ31, ZM60 and ZM21, are focusing on hot formability, on the attitude of the alloy to be formed and the effect of sheet thickness or initial microstructure [7-10]. No information at all can be found in the literature on high temperature formability of ZAM100 magnesium alloy.

In this framework, the present study aims at investigating the hot formability of ZAM100 sheets preliminary subjected to hot rolling in 3 steps at 2 final finishing temperatures, 320 and 420°C, in order to reach 2.1mm of thickness. Then, uniaxial tensile tests were carried out in extended ranges of temperature and strain rate. The experimental results have been analyzed in terms of flow curve shape, flow stress and flow strain to failure levels. They show that, in general, flow stress decreases and ductility increases with growing deformation temperature. The rolling temperature does not affect significantly the flow stress, while the strain to rupture is greater in the sheet rolled at 320°C. Thus, the lower rolling temperature enhances the hot formability. Finally, the peak flow stress (σ_p) dependence on strain rate ($\dot{\varepsilon}$) and temperature (T) was described by the well-known Garofalo's relationship [11], in the form:

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2017.12.250

$$\dot{\varepsilon} = A\left(\sinh(\alpha\sigma_p)\right)^n \exp(-Q_{HW}/RT) \quad (1)$$

where n is the stress exponent, Q_{HW} is the activation energy for high-temperature deformation, R is the gas constant, T is the absolute temperature, A and α are material parameters.

For comparison purpose, data by the same authors obtained by following the same procedure on AZ31 [12] and in torsion on ZEK200 [13] were also analyzed in the present study.

2. Material and experimental procedures

2.1. Material

The material used in the present work is ZAM100 magnesium alloy. The chemical composition of the alloy is reported in Table 1. ZAM100 is an advanced Mg alloy characterized by low content of alloying elements. This allows to improve plastic formability with respect to the traditional Mg alloys while ensuring high mechanical properties.

Table 1. Chemical composition of ZAM100 Mg alloy.

Elements	(wt. %)
Mg	Bal.
Zn	0.86
Mn	0.84
Al	0.62
Ca	0.1
Sr	0.07

The alloy has been supplied in form of 3.1 mm thick sheet produced by hot extrusion. In order to obtain the desired thickness of 2.1 mm, the sheets were hot rolled (HR) at two temperatures, namely 320 and 420°C, using a two-high mill stand; three passes have been performed with height reductions equal to 0.4, 0.4 and 0.2 mm, respectively. After rolling, the sheets have been water quenched.

2.2. Experiment procedures

The plastic flow behaviour of ZAM100 has been studied by means of uniaxial tensile tests. The tests were carried out under hot forming condition, at constant temperatures and strain rates as reported in Table 2. Specimens were obtained by water jet machining, with tensile axis parallel to the rolling direction, characterised by gauge width and length equal to 12 and 23 mm, respectively. Experimental tests have been performed using a servo-hydraulic testing machine equipped with a resistance furnace. Temperatures of the air inside the furnace and of the specimen have been monitored using two different K-type thermocouples. At least three repetitions for each test condition have been performed. To preserve the microstructure at fracture, samples were immediately unloaded and quenched in water.

Table 2. Process parameters of tensile tests.

$\dot{\varepsilon}$ (1/s)	$1x10^{-3}$	$1x10^{-2}$	$1x10^{-1}$
T(°C)			
300	X	X	X
350	X	X	X
400	X	X	X

3. Results and discussion

Figure 1 shows the microstructures of ZAM100 in the as-received condition and after rolling and water quenching. The microstructural observation, after hot rolling, revealed inhomogeneous fine grain size distribution. Twins are present in some grains.

The typical true stress–true strain curves, in the elastic and uniform plastic zones, obtained at various temperatures and strain rates, are shown in Fig.2. Irrespective of temperature and strain rate investigated, the flow stress increases with strain until a peak value is reached; then, the σ value decreases with increasing ε until failure.

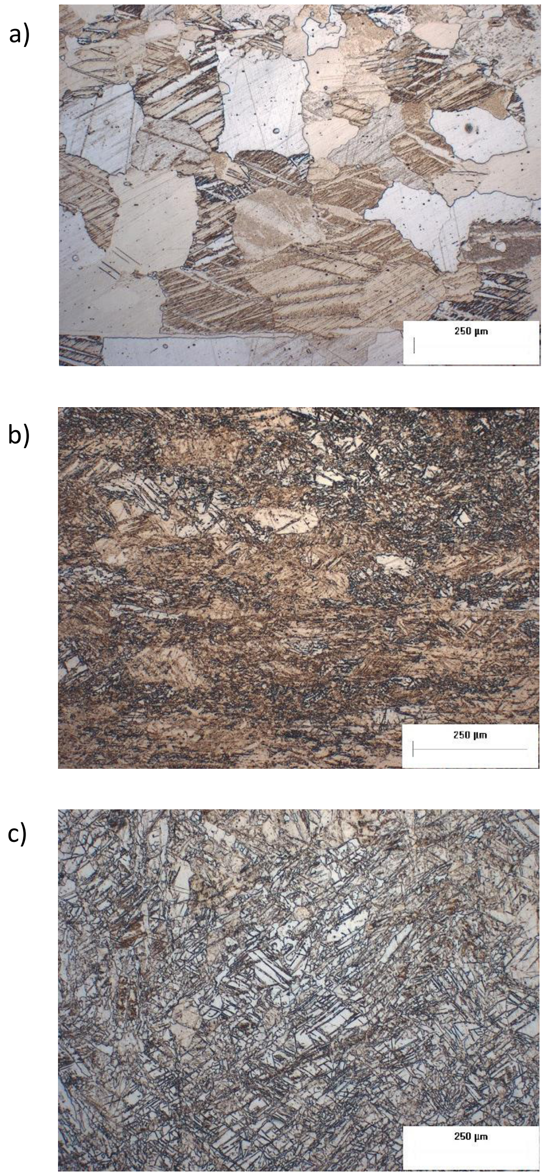

Fig. 1. Microstructure of ZAM100 (a) as received condition; (b) and (c) after hot rolling at 320 and 420°C, respectively.

The strain effect on the flow stress is maximum at the lowest temperature and highest strain rate investigated (300°C and 10^{-1} s^{-1}); it becomes ever less marked as temperature increases and strain rate decreases until the minimum effect is obtained at the highest temperature and lowest strain rate (400°C and $10^{-3}s^{-1}$) for both batches rolled at 320 and 420°C. At higher temperatures, the flow stress is almost independent of strain, because dynamic recovery can take place.

The influence of strain rate and temperature is also shown in figure 3a. It can be seen that, irrespective of the strain level, the flow stress decreases with increasing forming temperature and with decreasing strain rate. The temperature effect on σ is scarcely affected by strain rate; in particular, the σ_p value is almost halved as deformation temperature rises from 300 to 400°C. Finaly, no apreciable effect of the rolling temperature on flow stress is obsearved.

As far as the ductility of ZAM100 alloy is concerned, figure 3b shows the elongation to fracture A% as a function of temperature and strain rate. It appears that, irrespective of strain rate investigated, A% increases with deformation temperature. Such effect is more marked as the rolling temperature is equal to 320°C.

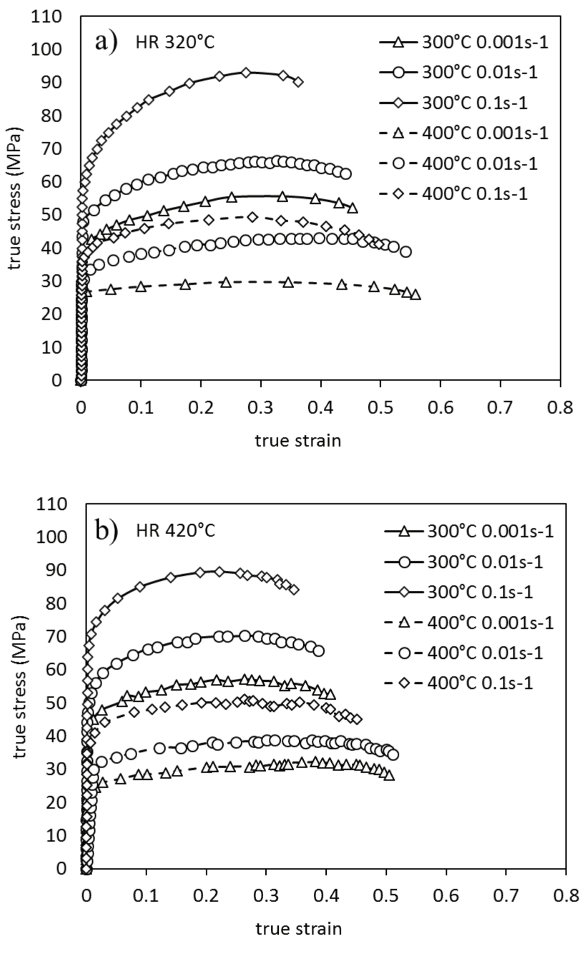

Fig. 2. Typical true stress– true strain curves for the hot rolled ZAM100 alloy at various temperatures and strain rates.

Figures 4 and 5 allow calculating the constitutive parameters of Eq. 1. For the ZAM100, the best-fitting procedure gave α= 0.0155 MPa^{-1}. The stress exponent n, calculated by plotting strain rate vs. sinh($\alpha\sigma_p$) was found to be 6.9 for the alloy rolled at 320°C, whereas it was 7.65 for the rolling temperature of 420°C (Figure 4). The activation energy, calculated by plotting sinh($\alpha\sigma_p$) as a function of 1000/T (Figure 5), was Q=152.2 kJ/mol and 175.7 J/mol for ZAM100 rolled at 320°C and 420°C, respectively. The values are almost equivalent to the one observed in ZEK200 [13], and are higher than that of self-diffusion of Mg (135 kJ/mol) or for diffusion of Al in Mg (143 kJ/mol). The coefficients provided in Eq.1 are summarized in Table 3.

Table 3. The constitutive parameters of equation 1 for ZAM100 hot rolled in two different temperature conditions.

Rolling Temperature	lnA (A in s^{-1})	n	Q (KJ/mol)	α (MPa^{-1})	R^2
320°C	25.22	6.90	152.17	0.0155	0.94
420°C	30	7.65	175.72	0.0155	0.98

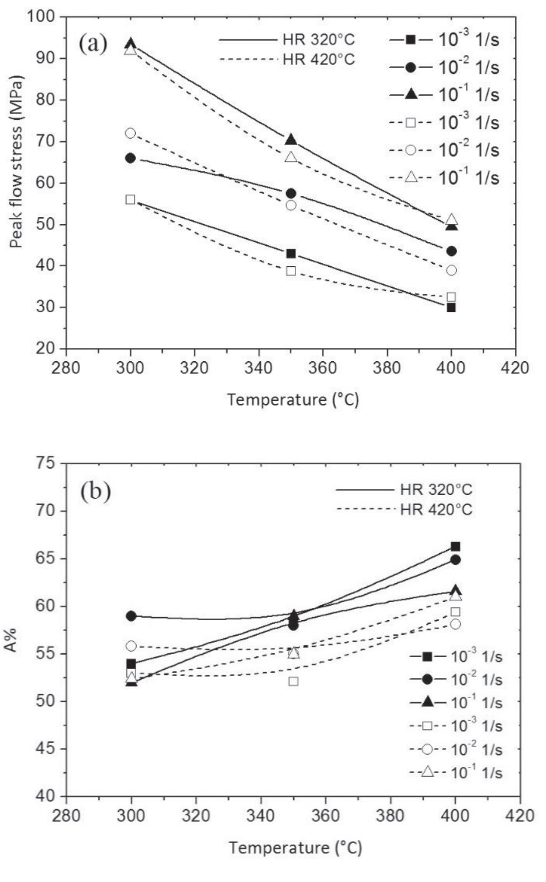

Fig. 3. (a) Temperature dependence of the peak stress at different strain rates; (b) elongation to fracture as a function of temperature.

Using the constants in Table 3, the peak flow stress values were calculated for the different processing conditions investigated. To this purpose, Figure 6 shows the comparison between experimental and predicted data calculated by Eq.1 for ZAM100 in both rolling temperatures.

An excellent correlation of all the calculated data can be seen; by analyzing the correlation coefficients, it appears that the peak stresses calculated by Eq.1 for the rolled alloy at 420°C are better predicted than the ones of ZAM100 HR at 320°C.

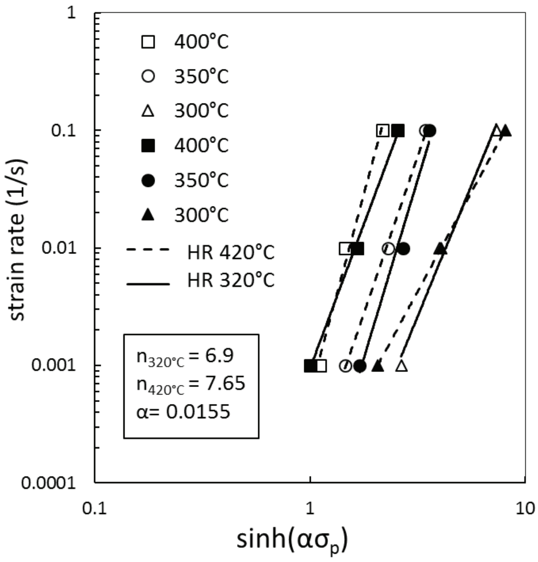

Fig. 4. Peak flow stress as a function of strain rate.

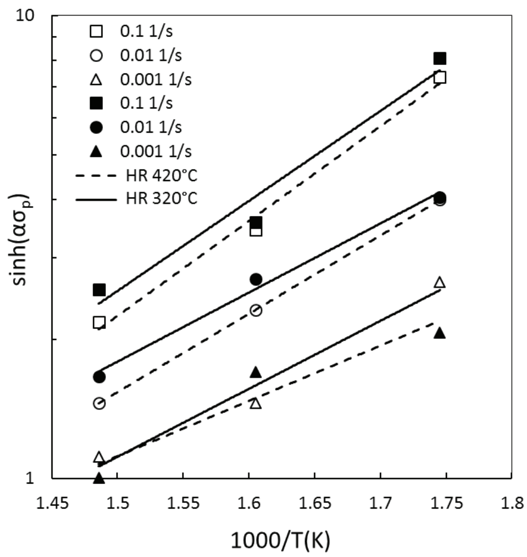

Fig. 5. Plot used for the calculation of the activation energy for high temperature deformation of ZAM100.

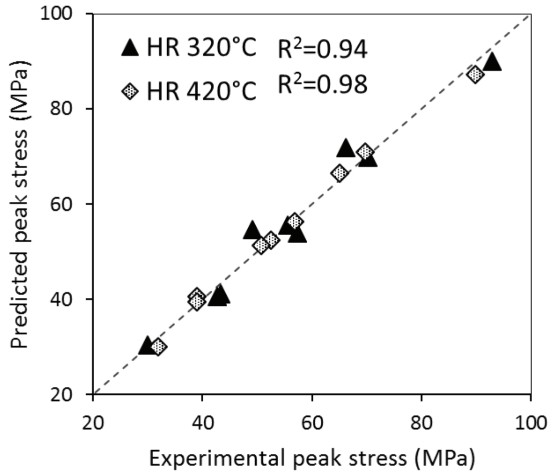

Fig. 6. Comparison between experimental and predicted peak stress for ZAM100 using the calculated parameters listed in Table 3;

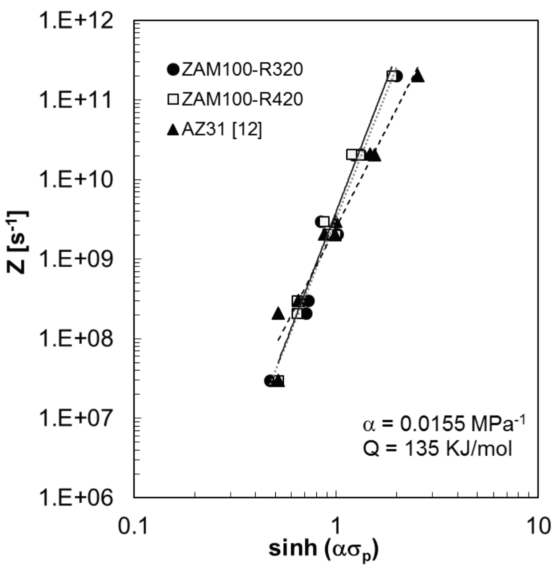

Fig. 7. Zener Hollomon parameter for the ZAM100 rolled at 320°C, 420°C and AZ31 [12].

Figure 7 shows the Zener-Hollomon parameter, also known as the temperature compensated strain rate $Z = \dot{\varepsilon} * exp(Q/RT)$, with Q=135 kJ/mol; as expected, almost all the experimental data quite closely align on a same straight line of slope n=6.5 for the ZAM100; for comparison purpose, the n value was equal to 5 for AZ31 [12]. Analysis of Fig. 7 clearly demonstrates that AZ31 with the presence of higher alloying elements corresponds to high peaks flow stresses, and should thus lead to the use of higher working load during forming.

4. Conclusions

The hot formability of a ZAM100 magnesium alloy, subjected to hot rolling at two different temperatures (320 and 420°C) has been investigated in the temperature and strain rate ranges varying from 300 to 400°C, and from 10^{-3} to 10^{-1} 1/s, respectively. Irrespective of the strain level, the flow stress decreases with increasing forming temperature and with decreasing strain rate. Irrespective of strain rate investigated, A% increases with deformation temperature. Such effect is more marked as the rolling temperature is equal to 320°C. The peak flow stress dependence on strain rate and temperature was described by the Garofalo's relationship. The calculated constitutive parameters has proven the validity of the proposed approach, even if the hot rolled alloy at 420°C showed a better predictive capability.

References

[1] Kleiner M, Geiger M, Klaus A. Manufacturing of Lightweight Components by Metal Forming. CIRP Annals - Manufacturing Technology 2003;52:521-42.
[2] Lee S, Chen Y-H, Wang J-Y. Isothermal sheet formability of magnesium alloy AZ31 and AZ61. Journal of Materials Processing Technology 2002;124:19-24.
[3] Spigarelli S, El Mehtedi M, Cabibbo M, Evangelista E, Kaneko J, Jäger A, Gartnerova V. Analysis of high-temperature deformation and microstructure of an AZ31 magnesium alloy. Materials Science and Engineering A 2007;462:197-201.
[4] Yukutake E, Kaneko J, Sugamata M. Anisotropy and non-uniformity in plastic behavior of AZ31 magnesium alloy plates. Materials Transactions 2003;44:452-457.
[5] Chen F-K, Huang T-B. Formability of stamping magnesium-alloy AZ31 sheets. Journal of Materials Processing Technology 2003;142:643-647.
[6] Zhang KF, Yin DL, Wu DZ. Formability of AZ31 magnesium alloy sheets at warm working conditions. International Journal of Machine Tools and Manufacture 2006;46:1276-1280.
[7] Spigarelli S, Ruano O A, El Mehtedi M, del Valle J A. High temperature deformation and microstructural instability in AZ31 magnesium alloy. Materials Science and Engineering A 2013;570:135-148.
[8] Spigarelli S, El Mehtedi M, Ciccarelli D, Regev M. Effect of grain size on high temperature deformation of AZ31 alloy. Materials Science and Engineering A 2011;528:6919-6926.
[9] Forcellese A, El Mehtedi M, Simoncini M, Spigarelli S. Formability and microstructure of AZ31 magnesium alloy sheets. Key Engineering Materials 2007;344:31-38.
[10] El Mehtedi M, Balloni L, Spigarelli S, Evangelista E, Rosen G. Hot workability and constitutive equations of ZM21 magnesium alloy. Key Engineering Materials 2008;367:79-86.
[11] Garofalo F. An empirical relation defining the stress dependence of minimum creep rate in metals. Transactions of the Metallurgical Society of Aime 1963;227:351-356.
[12] Forcellese A, Gabrielli F, Simoncini M, El Mehtedi M. Thickness effect on the formability of AZ31 magnesium alloy sheets. Key Engineering Materials 2011;473:313-318.
[13] Spigarelli S, El Mehtedi M, Ricci P. Hot working of the ZEK200 magnesium alloy. Materials Science Forum 2009; 604-605:212-222.